NUCLEAR ENERGY AND NUCLEAR CHARACTERISTICS (V)

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In a set of previous communications, I, II, III, IV (Dutta and others, 1963, 1964), we have analysed the formation and excitation energies of nuclei, available from the recent compilation works (Konig and others, 1962; Nuclear Data Sheets, 1962), and have found smooth relationships, to obtain the required magnitudes, to a fairly close approximation. The formation energy of nuclei, with optimum energy for any mass number, have been obtained by the combination of a basic curve of quadratic form in A, superposed by two periodic curves $F(Z)$ and $F(I)$ in nearly opposite phase. The deviation in energy of weakly bound isobaric nuclei is determined in terms of $\beta(\Delta N)^2$, i.e. $\beta(N-N_0)^2$, where β is the neutron-proton exchange energy and N_0 is the optimum neutron number for a mass number. These values can be calculated from available binding energy data, as shown in relations (*c*), and (*d*), in III. Since the fluctuation in optimum energy from a smooth quadratic relationship, never surpasses the magnitude of about 10 mev., in the whole range from -80 to -1800 mev., it is considered that such splitting up of the total energy into components is imperative, unlike the process implied in "one particle model". Weizsacker (1938) had suggested that in nuclear energy study, one should understand the deviation from the smooth course indicative of a liquid drop model. The collective nuclear model (Bohr and Mottelson 1953) also realises the importance of the basic liquid drop contribution.

Of the two potential energy curves $F(Z)$ and $F(I)$ shown in Fig. (2), IV, the potential curve $F(Z)$ primarily determines the energy of formation of weakly bound nuclei, as also the excitation energy, through close association of the obtained relations, with the maxima and minima positions of the curve $F(Z)$. Since the immediate determining factors in any transition, are the involved state functions, controlled mainly by the charge distributions, we have stamped the associated curve as $F(Z)$. The only other possible variable parameter for the associated periodic curve could be (I), the excess neutrons, which should determine the shape of the nuclei. The close correlationship of $F(I)$ with shape would be apparent from the fact that the quadrupole moment maxima are generally placed at the minima of the $F(I)$ curve. This would be elaborated further, later. It is also, to be realised on these grounds, that the energy change to the $F(Z)$ curve is immediate, followed by a deferred redistribution, corresponding to excess neutrons or shape, determined by the $F(I)$ function.

The minima positions of the controlling $F(Z)$ curve, in mass numbers, occur at 16, 40, 90, 140 and 208, corresponding to neutron-proton numbers as 8-8, 20–20; 50–40, 82–58, and 126–82. They correspond to the magic numbers of the shell model, 8, 20, 50 and 82 neutrons or protons, except that the proton number 50, corresponding to a mass number of about 118, is not a minimum of the $F(Z)$ curve. It is, on the contrary, the position of a maximum, along with the mass numbers 27, 60, 177 and 235. The absence of a shell closure or strong binding near 50-protons is corroborated on other considerations as follows:

When one observes the excitation energies of odd-mass nuclei (fig. 1, IV), it would be noted that all excitation energies jump up to large magnitudes at all other shell closure positions, except at 50-proton positions. The excitation energies of even-even nuclei also obtain subdued excitation energies in this region, compared to other shell closure positions. Absence of a shell closure at 50 protons is thus indicated. Already studied thermal (Flowers 1952) or fast neutron (Hughes *et al*, 1953) cross sections against neutron numbers point to the same direction. The plottings of deviations from Bethe-Weizsacker relation (Green, 1958) strongly confirms weak binding near 50 protons, in contrast to strong binding at 50 and 82 neutrons and 82 protons.

Further, the very obstinate nature of assymetric nuclear fission finds an easy explanation now, as the mass number in the region of 120, is a maximum of the periodic curve $F(Z)$ and thus would not be favoured for a transition. Indeed, Fong (1953, 1956) corrects the nuclear mass relation of symmetric fission product nuclei, such that it is less strongly bound than the assymetric fission product nuclei, and proceeds to justify the assymetry on shell model. Hill and Wheeler (1953), however, rules out the possibility of explanation on shell baisis and proposes assymetry on hydrodynamic consideration. As we have just noted, symmetric and assymetric fission products follow automatically on the basis of $F(Z)$ potential curve. It is also clear that the symmetric fission products, with a higher energy level, would be favoured with high excitation energies, as obtains in the case of dissociation of molecules, with constituents associated with excited energy.

Moreover, the argument of measured isotopic abundances in favour of magic numbers, when properly read, goes against the idea of 50-proton nuclei as being near a strongly bound position. One observes that the maximum of isotopic abundance generally tends to move to higher neutron-number isotopes as one moves to heavier elements, except that at the shell closure positions, even the lightest isotope obtains the largest abundance. It indicates the large probability of transition to these nuclei, on account of their low potential energy. Thus, the nuclei $18A^{40}$(99%) $20Ca^{40}$(97%); $38Sr^{88}$(83%) $40Zr^{90}$(52%); $56Ba^{138}$(72%) and $58Ce^{140}$ (88%), the heaviest and lightest isotopes of the two elements grouped together, obtain the large abundances shown, on account of their shell closure positions, while $50Sn^{120}$ obtains only 30% abundance and $52Te^{120}$ is rare (Kaplan, 1963). It does not favour any strong transition probability near mass number 120 with about 50 protons.

Further, on account of the close relationship (Dutta *et al* IV) between neutron-proton exchange energy β, with the excitation energy and hence also with the ionisation energy of nuclei, one would consider that the mass numbers on the maximum of the $F(Z)$ curve, which are weakly bound, particularly when β value itself is low, should have fewer isobaric nuclei. This is corroborated by very few isobaric nuclei in the region of mass number 155 to 200, around $F(Z)$ maximum at 177. At the shell closure regions, corresponding to mass numbers 16, 40, 90, 120, 140 and 208, the average numbers of tabulated (Konig, *et al*, 1962) nuclei are respectively 3.5, 4.5, 5.5, 3.5, 5.5, 5, respectively. The number of isobaric nuclei near mass number 60 another $F(Z)$ maximum position is also 3.5. It points out again proton-50 nuclei as not in strongly bound region.

The reason for considering proton 50 region as shell closure, is primarily the large number of stable isotopes, for the elements with charge values near 50, corresponding to mass numbers 115 to 135. Since the most strongly bound nuclei of any mass number is measured in terms of the smallness of the expression $\beta(\Delta N)^2$, it is apparent that if the rate of variation of N_0 is nearly as high as the rate of variation of N, for successive mass numbers, an element would remain in the nearly optimum condition of energy for a series of mass numbers, giving a large number of isotopes. The increase in the calculated values of N_0 with mass number may be obtained by relation (d, III). It is observed that the rate of increase of N_0 is approximately 0.4, 0.8, 0.4 and 0.6, near about the mass numbers 90 ($N = 50$), 118($Z = 50$),138 ($N = 82$) and 208($Z = 82$). The average number of stable isotopes in these regions are 5, 9, 5 and 4, in accordance with expectation. The number of isotopes is thus, not a criterion of strongly bound condition, unless the large value for the rate of change of N_0 can be considered to be a criterion for that and this evidently it is not, according to the above. The rate of increase of N_0 is actually determined by structural development.

The difficulty of the shell model, in view of the uncertainty of the 50-proton shell closure as also in view of the unsatisfactory explanation of magnetic and quadrupole moments, cannot be avoided by switching over to the collective nuclear model (A. Bohr and Mottelson 1953). Its correlation of excitation of even-even nuclei with the rotational energy expression, in the range of mass numbers 150 to 190, definitely fails for the nuclei $64Gd^{152}$, $74W^{180}$, and $78Pt^{190}$, in a systematic fashion. They are weakly bound even-even nuclei in this region by the criterion of $\beta(\Delta N)^2$ magnitude, and obtains a drop from the ratio of 3.3 for 2nd and Ist excitation energies to less than 2. This suggests explanation for the change in excitation energies here, to other causes than the change in rotational quantum numbers. A new orientation in the ideas about the structural development, is, thus necessary.

To understand the process of growth of nuclei, we note that the half periods of the periodic function $F(Z)$, mentioned before occur at steps of Z_0 values, which remain roughly constant at about 10.5 units of charge after two initial lower steps at mass numbers 16 and 40. Such small and nearly constant half period values of nuclear charge could not be accounted for by any form of evenly distributed neutrons and protons at appropriate distances, over continuously increasing size of nuclei. It compels one to suggest that the growth in nuclear structure should be in the form of quasi-crystalline development, with variable units to increase the size during a period of growth, gradually.

Such a process of growth is also envisaged by Wigner's(1933) ideas on the short range nuclear force. It had been suggested by Wigner and emphasised by Weizsacker (1938) and others that the rapid rise in bindings energy per nucleon of $2He^4$ from that of $1H^2$, through the nuclei $1H^3$ and $2He^3$ is on account of the increase in bonds between nucleons and the consequent closeness of internucleonic distance. Such large binding energy per nucleon as in $2He^4$ obtains again at $4Be^8$ and then from $6C^{12}$, onwards. The intervening nuclei from $2He^4$ upto $6C^{12}$, except $4Be^8$ have much lower binding energies per nucleon and must posses a more open structure, with less bonds per nucleon. The increase in binding energy of $2He^4$, $4Be^8$, $6C^{12}$ and onwards, would then be on account of doubling up character, such that the bonds per nucleon are increased. Nuclei like $6C^{13}$, $7N^{14}$, $8O^{17}$, which also obtain large binding energies per nucleon could be considered as doubling up of known nuclei, such that symmetry of structure is also maintained.

For further growth and maintenance of symmetry we could always consider the even-even nucleus as doubled up structure of two groups, as in $2He^4$ and $4Be^8$ and an odd mass nucleus as a composition of three groups of nuclei, generally, held by internucleonic bonds. The nucleons in each group sould also obtain spinning and orbital motion, on account of exchange of neutrons and protons to give the noucleus a liquid drop character.

Group formation as a recourse to the explanation of short range forces was suggested by Wefelmeyr (1937) and Fano (1937), in the form of an α-particle model of solid crystal type. Weizsacker (1938) had brought out the comparative advantages, of such model over one particle model. It was also proposed by Wheeler (1937) and rejected by him (1941), on account of some obvious inconsistencies. A larger nucleus is not likely to be built up with strongly bound units like α-particle, of nonflexible nucleonic content. The inconsistencies are often on account of that. It is more reasonable to build up larger nuclei with a nucleonic composition of 3, 4 and 5 units of charge and associated neutrons, which are all weakly bound, ($4Be^8$ would have been also weakly bound, if it were an open structure and not double up) and satisfy group association through internucleonic bondages, unlike the schemes with α-particles as interacting entities.

Such building up process gives us the cohesive forces of the proper order of magnitude also (Dutta *et al* 1962). This limitation in size of the small units helps us in understanding the periodic structure, through a process of rearrangement that keep the nucleons always compact and hence nearer the spherical shape. Such a process of structural growth also helps us in understanding the correlation between nuclear orbital and magnetic moments as also the quadrupole moments. This will be discussed in the following communication.

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